Neutron stars and quark matter

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Abstract.
Recent observations of neutron star masses close to the maximum predicted by nucleonic equations of state begin to challenge our understanding of dense matter in neutron stars, and constrain the possible presence of quark matter in their deep interiors.

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INTRODUCTION

Neutron stars – highly compact stellar objects with masses $\sim$ 1-2 $M_\odot$ (solar masses), radii of order 10-12 km, and temperatures well below one MeV – are natural laboratories to study cold ultradense matter [1]. Indeed, the inner cores of neutron stars are the only known sites where one could expect degenerate quark matter in nature. Figure 1 shows the cross section of a neutron star interior. The mass density, ρ, increases with increasing depth in the star. The crust is typically $\sim$1 km thick, and consists, except in the molten outer tens of meters, of a lattice of bare nuclei immersed in a sea of degenerate electrons, as in a normal metal. The matter becomes more neutron rich with increasing density, a result of the increasing electron Fermi energy favoring electron capture on protons, $e^- + p \to n + \nu_e$. Beyond the *neutron drip* point, $\rho_{drip} \sim 10^{11}\text{g/cm}^3 (= 2\times 10^{-4}\ \text{fm}^{-3})$, the matter becomes so neutron rich that the continuum neutron states begin to be filled, and the still solid matter becomes permeated by a sea of free neutrons in addition to the electron sea. At a density of order half nuclear matter density, $n_0 \simeq 0.16\text{fm}^{-3}$, the matter dissolves into a uniform liquid composed primarily of neutrons, plus $\sim$5% protons and electrons, and a sprinkle of muons.

The nature of the extremely dense matter in the cores of neutron stars, while determining the gross structure of neutron stars, e.g., density profiles $\rho(r)$, radii R, moments of inertia, and the maximum neutron star mass, M_{max}, remains uncertain. Scenarios, from nuclear and hadronic matter, to exotic states involving pionic [2] or kaonic [3] Bose-Einstein condensation, to bulk quark matter and quark matter in droplets, including superconducting states, as well as strange quark matter, have been proposed. Ultrarelativistic heavy ion collision experiments at RHIC, and soon at ALICE and CMS at the LHC, probe hot dense matter, from which one can gain hints of the properties of cold matter. The uncertainies in the properties of matter at densities much greater than n_0 are reflected in uncertainties in M_{max}, important in distinguishing possible black holes from a neutron stars by measurement of their masses, and in inferring whether an independent family of denser quark stars, composed essentially of quark matter, can exist.

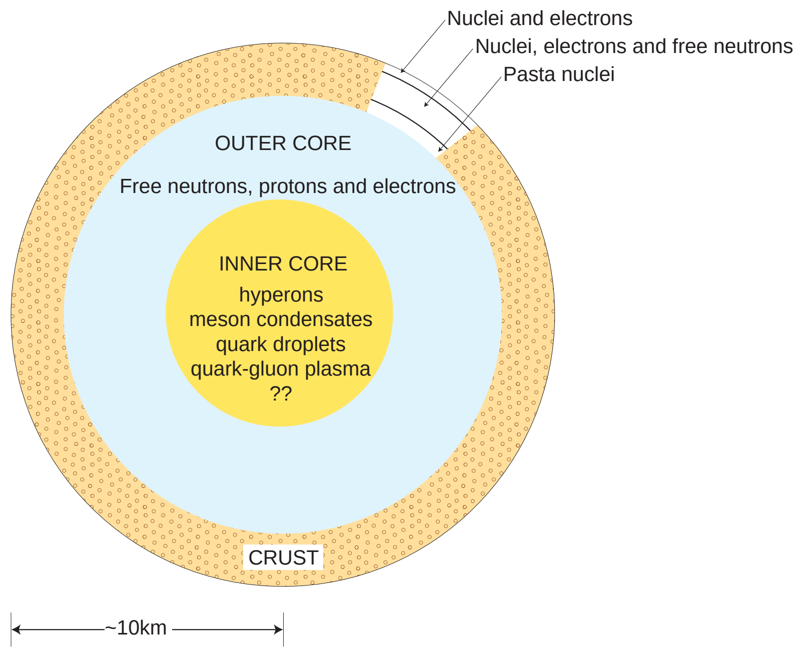

FIGURE 1. Schematic cross section of a neutron star.

NUCLEAR MATTER IN THE INTERIOR

The properties of the liquid near n_0 can be readily determined by extrapolation from laboratory nuclear physics. The most reliable equations of state of nuclear matter in neutron stars are based on extracting nucleon-nucleon interactions from pp and pn scattering experiments at energies below $\sim$ 300 MeV, constrained by fitting the properties of the deuteron, and solving the many-body Schrödinger equation numerically via variational techniques to find the energy density as a function of baryon number, e.g., [4, 5]. The most complete two-body potential is the Argonne A18 (with 18 different components, such as central, spin-orbit, etc., of the interactions).

Two-body potentials predict a reasonable binding energy of nuclear matter; however the calculated equilibrium density is too high. Similarly, two-body potentials fail to produce sufficient binding of light nuclei [6]. The binding problems indicate that one must take into account intrinsic three-body forces acting between nucleons, such as the process in which two of the nucleons scatter becoming internally excited to an intermediate isobar state (Δ) while the third nucleon scatters from one of the isobars. The three-body forces must increase the binding in the neighborhood of n_0, but, to avoid overbinding nuclear matter, they must become repulsive at higher densities. This repulsion leads to a stiffening of the equation of state of neutron star matter at higher densities over that computed from two-body forces alone.

Figure 2 shows the energy per baryon of neutron matter as a function of baryon density [5] with the A18 two-body potential, and Urbana UIX three-body potential, together with relativistic boost corrections (δv), accurate to order $(v/c)^2$. This equation of state, taking into account all two-nucleon data, and data from light nuclei, is currently

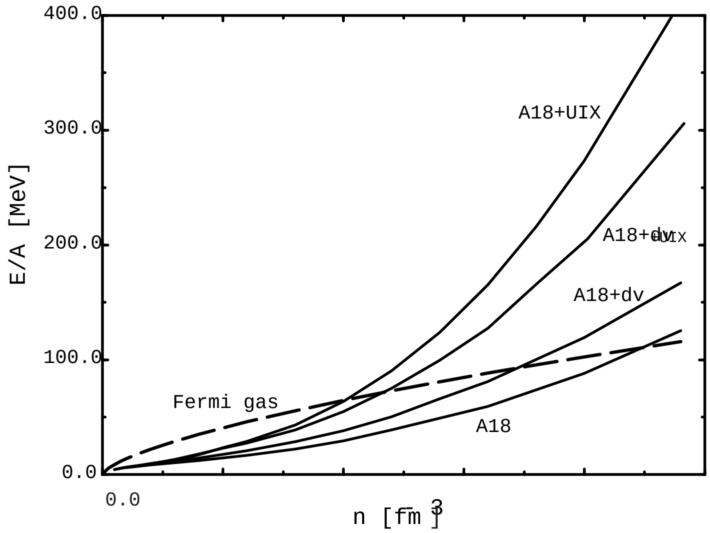

FIGURE 2. Energy per baryon of pure neutron matter as a function of baryon density, *n*, calculated with the A18 two-body potential with and without the Urbana IX (UIX) three-body potential, and lowest order relativistic corrections, δv. From [5].

the best available for $n \gtrsim n_0$. (Nuclear equations of state based on the more accurate “Illinois" three-body potentials [7] will be reported shortly [8].) One sees here the stiffening of the equation of state from inclusion of three-body forces, slightly mitigated by relativistic effects. Figure 3a shows the gravitational mass vs. central density for families of stars calculated by integrating the Tolman-Oppenheimer-Volkoff equation for the same equation of state as in Fig. 2, with beta equilibrium of the nucleons included. The maximum mass for the nucleonic equation of state, A18+δv+UIX, is $\simeq$ 2.2 $M_\odot$, marginally consistent with observed neutron star masses. By constrast, without three-body forces, the maximum mass is $\sim 1.6 M_\odot$, below some observed masses. The corresponding mass vs. radius of the families of models is shown in Fig. 3b; the radii of these models vary little with mass, and are in the range 10-12 km, except at the extremes.

An equation of state based on nucleon interactions alone, while accurately describing neutron star matter in the neighborhood of n_0, has several fundamental limitations. One should not expect beyond a few times n_0 that the forces between particles can be described in terms of static few-body potentials. Since the characteristic range of the nuclear forces is $\sim 1/2m_\pi$, the parameter measuring the relative importance of three and higher body forces is of order $n/(2m_\pi)^3 \sim 0.4n/fm^3$, so that at densities well above n_0 a well defined expansion in terms of two-, three-, four-, ..., body forces no longer exists. The nucleonic equation of state furthermore does not take into account the rich variety of hadronic (Δ, hyperonic, mesonic, etc.) and quark degrees of freedom in the nuclear system which become important with increasing density. Nor can one continue to assume at higher densities that the system can even be described in terms of well-defined “asymptotic” laboratory particles. As one sees in Fig. 3a, the density in the central cores rises well above n_0; equations of state and neutron star models based on consideration of nuclear matter alone should not be regarded as definitive.

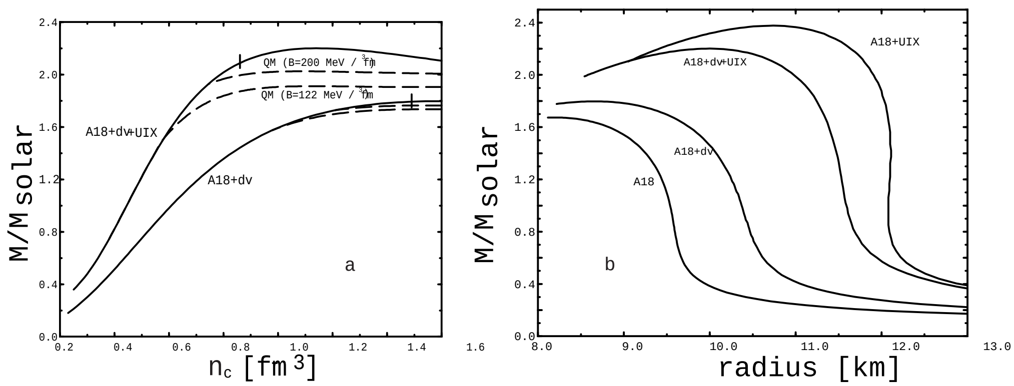

FIGURE 3. a) Neutron star mass vs. central baryon density for the equations of state shown in Fig. 2, including beta equilibrium. The curves labelled QM show the effect of allowing for a transition to quark matter described in the simple MIT bag model, with bag constants B = 122 and 200 MeV/fm^3. b) Mass vs. radius of neutron stars for the same models.

QUARK MATTER AND QUARK DROPLETS

Nuclear matter is expected to turn into a quark-gluon plasma at sufficiently high baryon density. Figure 3a shows effects of including quark matter cores, naively calculated in the simple MIT bag model, with bag parameter B =122 and 200 MeV/fm^3. Because of the well-known technical problems in implementing lattice gauge theory calculations at non-zero baryon density, we do not to date have a reliable estimate of the transition density at zero temperature or even a compelling answer as to whether there is a sharp phase transition or a crossover. Lattice approaches have included a canonical framework [9], which suggests a phase transition at $n \sim 3n_0$ in the hadronic phase to $\sim 10n_0$ in the quark phase; and the density of states method [10], which yields a transition at baryon chemical potential $\mu_b \sim$ 750MeV, as well as giving a triple point in the phase diagram at finite temperature. See also [11]. Representative field-theoretic calculations have been carried out in effective NJL theories [12]; in strong coupling qcd [13], and in terms of instanton overlap [14]. Although estimates of the density range of the transition, $\sim 5-10n_0$, are possibly above the central density found in neutron stars models based on nuclear equations of state, the question of whether the dominant degrees of freedom of the matter in the deep cores of neutron stars are quark-like remains open. In the absence of information about the equation of state at very high densities, the issue of whether a distinct family of quark stars with higher central densities than neutron stars can exist also remains open.

If pure neutron matter and quark matter are distinct phases with a first order transition between them, the transition occurs at nucleonic density n_q where the energy per baryon of quark matter crosses below that in neutron matter. However, the transition in neutron matter with a small admixture of protons and electrons in beta equilibrium must proceed through a mixed phase [15] starting at density below n_q. The mixed phase should consist of large droplets of quark matter immersed in a sea of hadronic matter [16, 17]. Formation of droplets is favored because the presence of s and d quarks allows reduction

of the electron density, and hence electron Fermi energy, and because it consequently permits an increase in the proton concentration in the hadronic phase. The onset of the droplet phase could, for favorable model parameters of the quark phase, be at a density as low as $\sim 2n_0$. A typical droplet is estimated to have a radius of ~ 5 fm, and contain ~ 100 u, and ~ 300 d as well as s quarks, and thus having a net negative charge ~ 150, but the results are very model dependent.

NEUTRON STAR MASSES

Observations of neutron star masses constrain the equation of state in the cores of neutron stars. The general rule obeyed by families of neutron stars generated at various central densities from a given equation of state is that the stiffer the equation of state, the higher is the maximum mass that a neutron star can have, but the lower is the central mass density, ρ_c at the maximum mass. Lower central density means that there is less room for exotic matter in the interior including π and K meson condensates, as well as quark matter. Observations of millisecond binary radio pulsars, consisting of two orbiting neutron stars, have permitted accurate determinations of their neutron star masses, as well as confirmed the existence of gravitational radiation; the masses lie in a relatively narrow interval, $\sim 1.35 \pm 0.04 M_\odot$ [18], a mass reminiscent of the Chandrasekhar core mass of the pre-supernova star. Were the maximum neutron star mass of order $1.4M_\odot$, the central densities could be sufficiently large to allow substantial exotica in the interior.

Even though the range of measured masses of neutron stars in binary neutron-star systems is tightly constricted, not all neutron stars must have such small masses. The constriction reflects the narrow evolutionary track that allows the two neutron stars to remain bound after their predecessors undergo supernova explosions [19]. A number of determinations of late of neutron star masses in compact binary x-ray sources call into question whether the maximum mass is indeed of order $1.4M_\odot$. The first is that of the neutron star in the x-ray binary, Vela X-1, with mass deduced to lie in the range $1.86 \pm 0.33 M_\odot$ [20, 21]. (Also [22] which infers $1.75M_\odot < M < 2.44M_\odot$.) The uncertainties in the measurement arise from uncertainties in the dynamic behavior of the atmosphere of the B-supergiant companion star, HD 77581; while the reported mass, if confirmed, would rule out very soft equations of state, e.g., those based on kaon condensation, the uncertainties in the determination do not allow one to make a definitive conclusion. A second measurement is that of the neutron star mass in the low mass x-ray binary, Cyg X-2, $1.78 \pm 0.23 M_\odot$ [23]. Such higher masses in x-ray binaries would allow for some exotic matter to be present in neutron stars.

More recently Nice et al. [24] have reported mass determination of the neutron star in the 3.4ms pulsar PSR J0751+1807 in a close circular (6h) binary orbit about a helium white dwarf. The measured neutron star mass is $2.1 \pm 0.2 M_\odot$, almost at the limit of compatibility with the nucleonic equation of state! The companion mass is $0.191 \pm 0.015 M_\odot$. While white dwarfs do not give rise to the uncertainties present in the Vela X-1 companion, the thermal structure of the white dwarf irradiated by the pulsar is incompletely understood [25].

Another very promising approach to measuring neutron star masses is through understanding the origins of the KHz quasiperiodic oscillations (QPO's) observed in low mass x-ray binary neutron star systems [26]. The power spectra of these sources are characterized by pairs of peaks with a nearly constant frequency difference. The QPO's arise from gas accreted from the companion star working its way through a disk down to orbits very close to the neutron star surface, where general relativistic effects are crucial. If, as is strongly suggested by detailed models [27], the upper QPO frequency ν_2 is that of orbital motion of the accreted matter in the innermost circular stable orbit about the neutron star, at radius $R_{\rm ISCO} = 6MG/c^2 = 3R_{\rm Schwarzschild}$, then one directly infers $M = c^3/12\sqrt{6}\pi G\nu_2$. For the QPO system 4U1820-30, with $\nu_2 \simeq 1070$ Hz [28], one would deduce a mass $\simeq 2.0M_\odot$.

Finally, Özel, analyzing the neutron star in the low mass x-ray binary EXO0748-676, a thermonuclear burst source, finds a mass $\simeq 2.1\pm0.28M_\odot$, and radius $R \simeq 13.8\pm1.8$km – on the outer edge of the radii predicted by the Akmal et al. equation of state. These results suggest that the equation of state may be even stiffer at lower densities, $\lesssim 4n_0$.

CONCLUSIONS

Observations of masses close to the maximum, $\simeq 2.2M_\odot$, predicted by the nucleonic equation of state begin to challenge our knowledge of the physics of neutron star interiors. The existence of high mass neutron stars immediately indicates that the equation of state must be very stiff, whether produced by interacting nucleons or other physics. Central densities are unlikely to be well above $\sim 7n_0$. If there is a sharp deconfinement phase transition below this density, then neutron stars could have quark matter cores as long as the quark matter is itself very stiff. Could M_{max} be larger? Given the equation of state up to a mass density ρ_f, the maximum possible mass is produced if the equation of state above ρ_f has sound velocity $c_s = \sqrt{\partial P/\partial\rho}$ equal to the speed of light [30]. The c_s predicted by the nucleonic equation of state [5] reaches c at $n \sim 7n_0$; modifying the physical input, e.g., by including further degrees of freedom such as hyperons, mesons, or quarks at densities in this neighborhood would lower the energy per baryon and tend to decrease the stiffness. Larger M_{max} would require larger c_s at lower densities; e.g., if one maintains the nuclear equation of state only up to $\rho_f = 2\rho_0$, then the maximum mass can be as large as 2.9 $M_\odot$ [31]. Such stiffening would lead to larger radii, perhaps more consistent with that reported for the neutron star in EXO0748-676 [29].

Nonetheless, quarks degrees of freedom – not accounted for by interacting nucleons interacting via static potential – are expected play a role in neutron stars. As nucleons begin to overlap, quark degrees of freedom should become more important, as stressed by Horowitz [32]. Indeed, once nucleons overlap considerably the matter should percolate, opening the possibility of their quark constituents propagating throughout the system (although near the onset of percolation valence quarks may prefer to remain bound in triplets, mimicking nucleons, and leaving the matter a color insulator) [33, 34]. Furthermore, the transition from hadronic to quark matter at low temperature is likely a crossover from BCS-paired superfluid hadronic matter to superfluid quark matter [35, 36]. A firm assessment of the role of quarks in neutron stars must await a better understanding of mechanisms of quark deconfinement with increasing baryon density.

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